Effect of heat leaks in platinum resistance thermometry

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The effect of heat leaks in platinum resistance thermometry is analyzed. An experimental method is proposed for estimating the magnitude of this effect. Results are reported for the measurement of the temperature of a hot, solid body under different heat-leak configurations. Design criteria for thermometers are presented which minimize the effect of such heat leaks.

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INTRODUCTION

Most devices for the measurement of the temperature of a hot body are composed of a sensing element as well as an agent for transmitting information from the sensing element to the ambient temperature region.[1] This agent involves an undesired heat leak from the sensing element to the ambient, which cools the sensing element below the temperature of the hot body. This phenomenon may be called self cooling, in analogy to self-heating, since in both cases the temperature of the sensing element differs from that of the measured body because of a heat flow across the finite thermal resistance between them.

The purpose of this paper is to propose a method for estimating the lower bound for the self-cooling difference between the temperature registered by the sensing element and the temperature of the hot body. This temperature difference can be surprisingly large under certain circumstances. For example, in an experiment to be described, a self-cooling temperature difference of 5 °C is found for a measured temperature of only 150 °C. Although the magnitude of the self-cooling temperature difference is, of course, dependent on the particular experimental arrangement, significant self-cooling temperature differences are quite common when measuring the temperature of a solid body.

In Fig. 1, we summarize schematically the considerations relevant to self-cooling. The temperature of the hot body differs from the temperature of the sensing element because of a heat flow across the finite thermal contact resistance R_C between them. The goal of the thermometer design which will minimize self-cooling effects is to have the sensing element temperature T_S approach the body temperature T_B in spite of the necessity of attaching conductive measuring leads to the outside ambient temperature T_A. Since, in general, R_C cannot be made sufficiently small, therefore the heat flow from the body via the sensing element and the leads to the outside will produce a non-negligible temperature drop across R_C. This temperature drop is the self-cooling temperature difference, which will be denoted by ΔT.

The magnitude of ΔT will depend strongly on several design features. A well designed thermometer has the following three characteristics: (i) radial heat flow to the leads via R_B is maximized (but only within the confines of the hot body), (ii) axial flow down the leads to the ambient via R_A is minimized, and (iii) contact resistance between the hot body and the sensing element via R_C is minimized. The first two characteristics tend to reduce the heat flow from the sensing element itself to the ambient. The third characteristic tends to reduce the temperature difference ΔT occasioned by a given heat flow from the sensing element.

For a thermometer deeply immersed in a flowing liquid, R_B and R_C can be made quite small and R_A can be made large. However, for the measurement of a solid body, R_B and R_C are many times larger than for the liquid and may therefore give rise to a large ΔT. Aside from the absolute error which will occur if ΔT is not accounted for, any change in the magnitude of R_B or R_C with temperature, or even with time, will give rise to a change in ΔT. The neglect of this change in ΔT will lead to errors in the relative accuracy between different temperature measurements. Moreover, as one goes to elevated temperatures, ΔT becomes even larger with T_S lagging farther and farther below T_B.

The effect of self-cooling is very similar to "stem losses."[2–5] Stem loss refers to the general cooling of the *region* of the thermometer by heat conducted from the body via the entire stem, including the sheath, leads, etc. Self-cooling involves only a small portion of this stem loss, namely, that portion which flows *via* the sensing element. This much smaller heat flow can strongly affect the measured temperature of the sensing element when R_C is not sufficiently small, even though the body temperature is virtually unaffected.

In this context it is noteworthy that workers dealing with measurements at elevated temperatures have evinced considerable concern about possible errors ascribed to "stem losses." Several workers[2–4] have noted that tests for stem losses do not give satisfactory results, i.e., a measured temperature independent of the depth of immersion of the thermometer. These errors may in fact be ascribed to self-cooling effects and an estimate of their magnitude by the method proposed here should now be possible.

It should be noted that the phenomenon of self-cooling is not limited to platinum resistance thermometry. Although the study presented here has been performed on platinum resistance thermometers, it is anticipated that similar self-cooling effects will occur for other thermometer means. However, the specifics of such problems must await further study.

In Sec. I, the basic concepts of self-cooling are discussed, with particular emphasis on its relation to self heating and the use of the latter in estimating self-cooling temperature differences. Several experiments demonstrating the effect are described in Sec. II. Finally in Sec. III, design criteria are deduced from the experimental results and a test of such a design is described.

I. BASIC CONCEPT OF SELF-COOLING

The use of a temperature sensor with leads to the outside environment gives rise to a small heat flow $\dot{Q}$ from the hot body B being measured via the sensing element S and the leads to the outside environment (see Fig. 1). This flow $\dot{Q}$ is supposed to be kept small enough both (i) to leave the temperature of B virtually unaffected, as well as (ii) to keep the temperature drop from B to S sufficiently small so as to bring S close to thermal equilibrium with B. In fact, the accomplishment of the second goal requires keeping the product $\dot{Q}R_C$ small because

$$T_S \leq T_B - \dot{Q}R_C. \tag{1}$$

The similarity of self-cooling to self-heating arises from the fact that at least part (and usually most) of the Joule heat Q_J generated at the sensing element is dissipated via R_C to the body. The consequent temperature difference constituting the self-heating effect will be

$$T_S \leqslant T_B + \dot{Q}_J R_C, \tag{2}$$

in close analogy to Eq. (1). The identification and elimination of self-heating effects is readily accomplished since one can change $\dot{Q}_J$ almost at will. By contrast, for self-cooling, even to estimate $\dot{Q}R_C$ is a formidable problem.

We here propose to use the *in situ* observed self-heating coefficient as a tool in this estimate. A simple *in situ* self-heating coefficient determination will provide a lower limit to the value of R_C from Eq. (2). There remains only to make a rough estimate of $\dot{Q}$ in (1), in order to have a lower bound on the self-cooling temperature difference.

As a numerical example consider a solid body at 150 °C as measured by a commercial capsule platinum resistance inserted into a hole drilled into the body, with 0.3-mm-diam platinum leads extending into the outside environment. A rough but adequate estimate of $\dot{Q}$ is given by

$$\dot{Q} = \kappa A \frac{\Delta T}{\Delta x} \simeq 2 \times 10^{-2}\ \mathrm{W}, \tag{3}$$

where the effective lead length Δx is taken as 5 cm to reach the environment temperature of 25 °C and where heat dissipation has been assumed to be entirely via conduction along the leads.

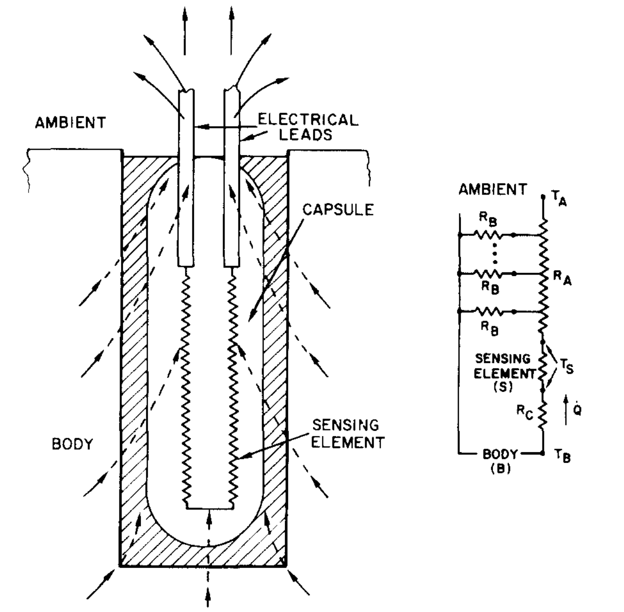

FIG. 1. Schematic of the elements relating to self-cooling. Heat $\dot{Q}$ flows from the body B whose temperature T_B is being measured via R_C to the sensing element S at temperature T_S and then to the outside ambient temperature T_A via the stem and leads R_A. The thermal resistances R_B denote the path of radial heat flow from the body to the ambient not via the sensing element.

This is combined with self-heating data to give an estimate of the self-cooling error

$$(T_B - T_S)_{\mathrm{sc}} = \dot{Q}R_C \geq (T_S - T_B)_{\mathrm{sh}}\dot{Q}/\dot{Q}_J, \tag{4}$$

where the subscripts sc and sh refer to self-cooling and self-heating effects, respectively. A typical value listed by the manufacturer for the self-heating coefficient $(T_S - T)_{\mathrm{sh}}/\dot{Q}_J$ is 1 °C/50 mW, provided that the sensor is placed in a stream of oil flowing at a speed of 3 ft/min. This would lead to an estimate of 0.4 °C for the self-cooling error. However, the self-heating coefficient *in situ* yields a coefficient of order 1 °C/10 mW, as we found by direct measurement. Thus, the actual self-cooling temperature difference is closer to about 2 °C.

II. EXPERIMENT

In this section we describe a series of experiments which indicate the existence and estimate the magnitude of self-cooling temperature differences.

A. Relative self-cooling effects

A copper cylinder, 3 cm in diameter and 6 cm long, was evenly wrapped with nickel-chrome heating wire in a single clockwise-counter-clockwise layer. Three holes of 0.2 cm diameter and 3 cm depth were drilled symmetrically about the central axis of the cylinder. A model 146L-2 Rosemount sealed, platinum resistance thermometer (PRT) was inserted in each hole (1.9 mm diameter and 18 mm length). The PRT's were calibrated by Rosemount to 0.1 °C absolute and to 0.01 °C relative accuracy. One of the three PRT's was used to

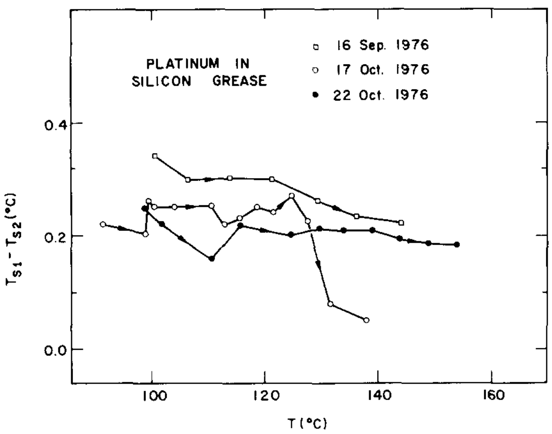

FIG. 2. Temperature differences $T_{S1}-T_{S2}$ between two equivalently located platinum resistance thermometers as the block temperature T was changed. The thermal contact between the thermometer and the inside hole surface in the copper block was via a silicon grease having relatively good thermal conducting properties. Each run was performed on the indicated date.

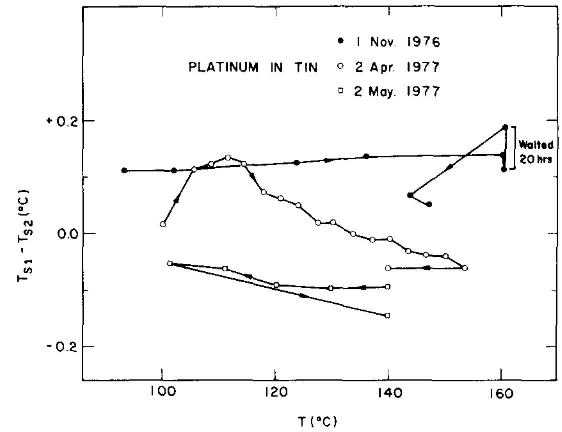

FIG. 3. Same as Fig. 2 but with tin as medium for making good thermal contact with the body. The first two runs are without outgassing the indium (solid and open circles). The third run is slightly improved because the indium was outgassed for 7 h before this last measurement.

stabilize the cylinder temperature to ±0.01 °C/h. The remaining two PRT's were compared to each other to evaluate relative self-cooling errors. The entire system was enclosed in a vacuum of 5×10^{-6} Torr.

1. Run #1

The medium used to make thermal contact between the PRT capsules and the copper cylinder was a commercial silicon grease used for making good thermal contact between transistors and their heat sinks. In Fig. 2, a plot is shown of the difference between the two measured temperatures $T_{S1}-T_{S2}$ vs their average temperature over the range 90°–160 °C. The differences ranged from 0.34°–0.05 °C, well beyond either calibration errors or actual temperature differences.

2. Run #2

The medium used was metallic tin. The PRT's were inserted into the holes filled with molten tin. Figure 3 shows the resultant measured temperature differences, ranging from 0.19° to −0.06 °C, as shown by the open and solid circles. The improvement is not significant.

3. Run #3

The entire system from run #2 was heated to 240 °C to melt the tin. The vacuum level fell drastically and outgassing of the tin stopped only after seven hours at 240 °C. The subsequently measured temperature differences are shown as open squares in Fig. 3, and are hardly improved, ranging now from −0.05 to −0.14 °C.

The three runs just described demonstrate that for measuring a hot solid body, the achievement of adequately good thermal contact (small enough R_B and R_C) is a considerable problem. Even the extreme measures of run #3 were not sufficient to eliminate relative self-cooling temperature differences. It is reasonable to suppose that the existence of such large relative temperature differences is an indication of even much larger absolute temperature differences. This was in fact demonstrated to be so in the experiment described in the next section.

B. Absolute self-cooling effects

A copper cylinder, 10 cm in diameter and 20 cm long was heated as before. A single hole 1.5 cm diameter and 13 cm deep was drilled along the central axis and filled with oil. A highly reflecting cover with a 2 mm hole at the center prevented most heat losses from the upper surface. The copper cylinder was heated to obtain a stable temperature of 150 °C.

Measurements were made of the absolute temperature versus the depth of immersion L, where $L = 0$ represents the PRT capsule completely immersed but the leads entirely exposed to the air. Three different sets of measurements were made with the same PRT, but with leads of different material and thickness attached in each case. The results are shown in Fig. 4. These measurements confirm the existence and estimate the magnitude of self-cooling temperature differences in using conventional PRT's.

III. DESIGN CRITERIA FOR AVOIDING SELF-COOLING TEMPERATURE DIFFERENCES

As seen from the experiments of Sec. II, it does not appear to be promising to attempt to substantially reduce R_C. Rather, since the self-cooling effect depends on $\dot{Q}R_C$, one must find some effective means of reducing $\dot{Q}$.

The most promising approach for reducing $\dot{Q}$ is to increase the thermal resistance of the leads. Platinum leads are six times more resistant to heat flow than copper and constantan wire leads are three times more resistant than platinum. Thus, the use of copper leads, as is often done commercially,[6] may be an unnecessary cause of large self-cooling effects. A further substantial improvement is accomplished by reducing the lead

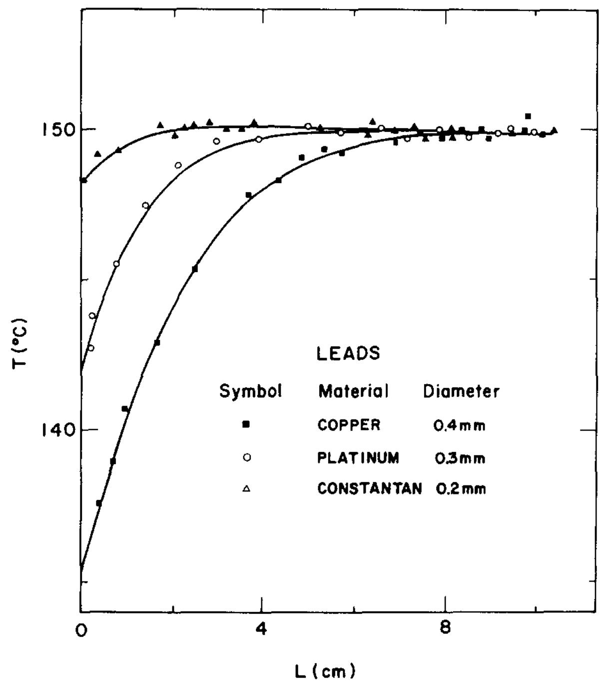

FIG. 4. Direct measurement of self-cooling temperature differences vs depth of immersion for three different sets of lead materials and diameters. The self-cooling temperature difference is quite large for 0.3-mm platinum and overwhelming for 0.4 mm copper, whereas for 0.2-mm constantan it is almost negligible.

diameter, because $\dot{Q}$ decreases as the square of the diameter. Naturally, the mechanical strength will suffer from the latter change, but one must choose between higher accuracy or greater mechanical strength. It should be kept in mind that the increase of the electrical resistivity of the leads to a value comparable to that of the sensing element is a potential source of error. However, this source of error can be completely avoided by the use of four leads rather than two since this insures that the resistance of the leads is not part of the measured value.

To demonstrate the improvement possible with the above design criteria, a standard 146L-2 Rosemount thermometer was modified. The two platinum leads were replaced by four 1 cm lengths of constantan wire 0.025 mm in diameter. These were in turn continued via four standard 0.3-mm platinum wires to the outside environment. The fragile 1 cm section of four constantan

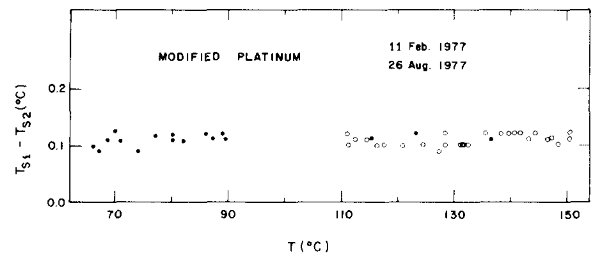

FIG. 5. Measurement of temperature difference T_{S1}-T_{S2} between two different PRT's whose leads were modified to offer a maximum decrease of self-cooling effects.

wires was embedded in insulating zirconia such that the overall zirconia constantan combination had a diameter of 0.15 mm. Since the thermal conductivity of the zirconia is about the same as constantan, this 1 cm section improved the thermal resistance of the leads by over a factor of 100.

Figure 5 shows the results of measurements by two such modified PRT's with only the capsule inserted into the hole in the copper block, and the constantan leads being outside the hole. The difference between the two measured temperatures is plotted versus the temperature of the copper block.

A set of about 200 measurements extending over a 6-month period show an uncertainty of ±0.01 °C, which was the accuracy of the electrical measuring instruments used. Thus, there is no trace of the self-cooling effects found in Sec. II with conventional leads.

In summary, the avoidance of self-cooling effects requires careful attention to thermometer design, in view of the many subtle pitfalls. The method here proposed for estimating the magnitude of the self-cooling temperature difference should be of considerable use in the design of PRT's.

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[6] See, for example, Leeds and Northrup 8920 series industrial type PRT having 24 AWG copper lead wires; Rosemount model 146MB having 28 AWG copper lead wires.